

# 30 YEARS OF OPERATIONAL OCEAN WAVE FORECASTING AT FLEET NUMERICAL METEOROLOGY AND OCEANOGRAPHY CENTER

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## 1. INTRODUCTION

Forecasting surface waves on the ocean is a problem of great practical interest, as sea states impact virtually all aspects of naval operations as well as a variety of commercial maritime activities. For example, accurate ocean wave forecasting is a key prerequisite for enabling optimum-track ship routing and ensuring the safety of lives and property at sea. Thus, ocean wave forecasting has been a priority for the U.S. Navy, and Fleet Numerical Meteorology and Oceanography Center (FNMOC) has pioneered the application of operational ocean wave models, dating all the way back to the 1960s.

## 2. OCEAN WAVE MODELS

FNMOC employed singular wave models operationally from the mid 1960s through the mid 1970s (Hubert, 1964; Hubert and Mendenhall, 1970; Schwartz and Hubert, 1973). These very simple models used empirical growth curves to predict only the significant wave height and kept track of only the dominant swell. They were followed by the Spectral Ocean Wave Model (SOWM), which was a result of the observational and theoretical work of W.J. Pierson and coworkers (Pierson *et al.*, 1966).

A regional implementation of the SOWM became operational at FNMOC for the Mediterranean Sea in 1974 (Lazanoff *et al.*, 1973). A year later, the SOWM became operational for the Northern Hemisphere (Lazanoff and Stevenson, 1975). These models were the world's first operational spectral ocean wave models, and were forced by winds produced by a northern-hemisphere planetary boundary layer model (PBLNH) driven by synoptic fields from the Fleet Numerical Northern Hemisphere Primitive Equation (PE) model (see Kesel and Winninghoff, 1972). The SOWM ran on icosahedral gnomonic grids, where grid lines are great circle routes. This was done to simplify the propagation of swell energy, as no spatial interpolations were needed. The SOWM was also used to produce a twenty-year Northern Hemisphere wave climatology (Lazanoff and Stevenson, 1978) that was valuable in a wide variety of naval and commercial applications throughout the 1980s.

When the Navy Operational Global Atmospheric Prediction System (NOGAPS; see Hogan and Rosmond, 1991) replaced the Northern Hemisphere PE model in the early 1980s, NOGAPS synoptic fields became the driving mechanism for PBLNH and thus SOWM. In 1985, the Global Spectral Ocean Wave Model (GSOWM), forced by surface winds from the Global Surface Contact Layer Interface (GSLI) model driven by NOGAPS synoptic fields, replaced the Northern Hemisphere SOWM as the operational wave model at FNMOC (see Clancy *et al.*, 1986). Although its wave

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growth and dissipation formulations were the same as SOWM, the GSOWM ran on a 2.5° spherical grid and used an energy conserving interpolation method for swell propagation rather than the icosahedral gnomonic grid approach. The GSOWM also increased the angular resolution of the predicted directional wave energy spectra from 30° to 15°. Both models used the same 15 bins to represent frequency space, accommodating wave periods ranging from about 3 seconds to about 26 seconds. GSOWM gave the Navy its first global ocean wave forecasting capability.

As part of the operational testing process, wave-height predictions from the Northern Hemisphere SOWM and the GSOWM were compared with observations from moored buoys along the east and west coasts of the continental U.S. and Hawaii. Results indicated that GSOWM was clearly more skillful than SOWM (see Table 1). Later, as the boundary layer formulation in NOGAPS was improved, the GSCLI model was dropped and GSOWM was forced by winds produced directly by NOGAPS. The GSOWM continued to serve the Navy's global wave prediction needs until 1994.

### **3. THE SPECTRAL WAVE MODEL PREDICTION (SWAMP) STUDY**

By 1985, and as discussed by Cox and Cardone (2002), there were a number of wave models being developed around the world, including MRI (Japan), NOWAMO (Norway), GONO (The Netherlands), BMO (UK), HYPA (Germany) and ODGP (US). The Sea Wave Modeling Project (SWAMP) study (SWAMP Group, 1985) was an attempt to compare the different wave models under seven theoretical wind conditions. At about the same time, Klaus Hasselmann and others were developing the theory of nonlinear wave interactions (see

Hasselmann *et al.*, 1985). First-generation wave models, such as SOWM and GSOWM, ignored these nonlinear wave interactions, which provide the mechanism for transferring wave energy from high-frequencies where wind input is dominant to lower frequencies where there is little or no energy extracted directly from the wind. Rather the wind input and dissipation formulations in first-generation models were adjusted to reproduce empirical growth curves. This approach worked well in open ocean conditions, but had limitations in fetch and duration limited conditions. In second-generation models the spectra is parameterized by a single slowly varying spectral parameter, such as peak frequency. This worked well for slowly changing wind forcing, but not in situations with strong non-uniform winds fields, such as produced by tropical cyclones, cold fronts, and mid-latitude storms.

The results of the SWAMP study clearly showed that both first and second-generation models had significant shortcomings, and this led to the development of the first third-generation wave model, WAM (see WAMDI Group, 1988), which parameterized nonlinear wave interactions from the full directional wave energy spectrum (Komen *et al.*, 1994). Although parameterization of the nonlinear wave interactions was computationally expensive, advances in supercomputer technology made it practical to run WAM operationally by the early 1990s.

### **4. THIRD-GENERATION WAVE MODELS**

In 1990, and as discussed by Clancy and Wittmann (1990), the Mediterranean SOWM model at FNMOC was replaced by WAM running at 0.25° resolution and forced by the Navy Operational Regional

Atmospheric Prediction System (NORAPS; Hodur, 1987). Although, WAM was too expensive to run at FNMOC on a global scale at that time, subsequent replacement of the CDC Cyber 205 supercomputer at FNMOC with a Cray C90 in 1992 provided the necessary computational power to enable a global WAM implementation. Global WAM on a 1° spherical grid replaced GSOWM as the FNMOC operational global wave model in 1994 (Wittmann and Clancy, 1994). In the late 1990's, WAM was also implemented as a high-resolution regional model in coastal areas and semi-enclosed basin, driven by the Coupled Ocean/Atmospheric Mesoscale Prediction System (COAMPS; see Hodur, 1997). The WAM Users Group provided upgrades and support during this time.

In 2001, FNMOC replaced the Cray C90 with a cluster of SGI Origin 2000 and Origin 3000 machines. These distributed-memory computers contained many hundreds of scalar processors, and required models to use the Message Passing Interface (MPI) routines to achieve highest efficiency (Wittmann, 2002). The new third-generation wave model, WaveWatch III (Tolman, 1990), was optimized with MPI for distributed memory machines, and also had an improved wave propagation scheme to handle the propagation of swell over long distances. In August 2001, following a formal operational test, FNMOC replaced all global and regional implementations of WAM with WaveWatch III (Wittmann, 2002). The operational test results from January and February of 2000 (Table 1) show the WaveWatch III and WAM root-mean-square errors to be very close.

However, the improved swell propagation and ongoing upgrade path for WaveWatch III made it a desirable long-term solution. Dr. Hendrik Tolman and his coworkers at the National Centers for Environmental Prediction (NCEP) continue to make model improvements, which are passed on to FNMOC and the larger WaveWatch III user community.

The global WaveWatch III implementation at FNMOC was upgraded to run on a 0.5° spherical grid in the fall of 2002, with wind forcing provided by NOGAPS at comparable resolution.

## **5. LONG-TERM TREND IN FNMOC WAVE MODEL ACCURACY**

Table 1 below provides a synopsis of the trend in FNMOC wave model accuracy over the past 20 years. Although data sources and verification regions are not completely uniform over the period, the downward trend in root-mean-square error (RMSE) is obvious and significant. The errors in mid-latitude wintertime wave-height predictions today are more than a factor of three smaller than 20 years ago. Of course, this trend has been due to improvements in both the wave models and the numerical weather prediction models that drive them. As the NOGAPS model continues to improve, and with commencement of operational assimilation of wave-height data into WaveWatch III in the near future, these errors are expected to come down even more, as FNMOC strives to provide the most accurate representation of ocean waves possible to its Fleet customers.

**Table 1**  
**Combined North Atlantic/North Pacific Verification Results for 6-Hour Forecasts from Northern Hemisphere/Global Wave Models Operational at FNMOC in the Past 20 Years**

Model	RMSE (m)	Period	Verification Data	Reference
SOWM	1.92	Jan 1985	Moored Buoys	Clancy <i>et al.</i> , 1986
GSOWM	1.36	Jan 1985	Moored Buoys	Clancy <i>et al.</i> , 1986
GSOWM	0.94	Mar 1992	Moored Buoys	Wittmann and Clancy, 1994
WAM	0.74	Mar 1992	Moored Buoys	Wittmann and Clancy, 1994
WAM	0.65	Jan/Feb 2000	Moored Buoys	Wittmann, 2002
WaveWatch III	0.67	Jan/Feb 2000	Moored Buoys	Wittmann, 2002
WAM	0.63	Jan/Feb 2000	ERS-2 Altimetry	Wittmann, 2002
WaveWatch III	0.58	Jan/Feb 2000	ERS-2 Altimetry	Wittmann, 2002

## 6. SUMMARY AND OUTLOOK

Reflecting the importance of sea state on naval operations, FNMOC has been at the forefront of operational ocean wave forecasting for over 30 years. These efforts began with very simple "singular" wave models in the 1960s and progressed through ever more complex spectral ocean wave models from the mid 1970s up to the present. A variety of steadily improving numerical weather prediction models and associated planetary boundary layer parameterizations provided the wind forcing for these models. The combined effect of improvements in both the wave models and the meteorological models reduced root-mean-square wave-height forecast errors by a factor of more than three over the past 20 years.

Although the traditional needs for sea state forecasts, such as hazard avoidance and

optimum track ship routing, remain important to the Navy, entirely new requirements have arisen. For example, near-shore wave and surf forecasts are required in support of amphibious landings, covert insertion of special operations forces, and logistics-over-the-shore operations. These challenges are being met with the FNMOC WaveWatch III implementations providing deep-water boundary conditions to the Distributed Integrated Ocean Prediction System (DIOPS) (Wakeham *et al.*, 2002). DIOPS employs the Simulating Waves Nearshore (SWAN) model (Booij *et al.*, 1996) shallow water wave model and the Delft 3D surf zone model (Ris, 1997) to forecast near-shore wave and surf conditions for naval applications.

Finally, the Navy's roadmap for the future, Sea Power 21 (see Clark, 2002), has important implications for operational ocean wave forecasting. In particular, the Sea

Basing component of the Sea Power 21 doctrine calls for the capability to accommodate significant combat forces for extended periods of time on vessels comprising a "sea base" located just offshore from an adversary nation. Clearly, these sea base vessels, and the entire Sea Basing concept, will be at the mercy of the elements, especially sea state. Thus, operational ocean wave forecasting will become even more critical to the Navy of the future.

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